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Effect of fabric orientation and impact angle on the erosion behavior of high-performance thermoplastic composites reinforced with ductile fabric

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ABSTRACT

How composites reinforced with plain-weave polybenzoxazole (PBO) fibers were eroded by solid particles was investigated. By evaluating the erosion rates of plain polymers and these composites at various impact angles ($\alpha=15$–$90°$), we confirmed that the polymers and their composites were ductile. The relationship between erosion behavior and fabric orientation from an energy perspective was studied, and our experimental results agreed well with our analytical results showing that the erosion behavior did not depend on fabric orientation. Using these results and scanning electron micrographs, a mathematical model was produced and it was used to predict the erosion rates of ductile materials. To verify this model, the theoretical and measured erosion rates of three high-performance ductile-fabric-reinforced thermoplastic composites were compared, showing that our mathematical model can accurately characterize their erosion behaviors.

1. Introduction

Once molded, fiber-reinforced plastics (FRPs) containing thermosetting resin cannot be reformed [1]. Because of this limitation, these plastics are typically disposed of in landfills, which may cause serious environmental pollution. However, the staggering growth of FRP use is fading, and fiber-reinforced thermoplastics (FRTPs)—which are easier to recycle—are slowly displacing FRPs. FRTPs are better materials for many parts in cars and airplanes, among other applications, because of their specific properties, high strain to failure, and high toughness [2,3]. Some parts of these vehicles reach high velocities (such as the part near aircraft engine or helicopter propellers) and thus produce high temperatures, so they cannot use composite materials made from normal thermoplastic. An attractive candidate for such applications, however, is polyetherimide (PEI): a high-performance amorphous thermoplastic polymer with a glass transition temperature of $\sim$220 °C, high heat resistance, and excellent mechanical properties [4]. Unfortunately, super engineering plastics such as PEI and polyetheretherketone (PEEK) have considerably higher melt viscosities than thermosetting resins and normal thermoplastics, such as polypropylene (PP), because of their high molecular weight, which makes it more difficult for the resin to impregnate the fabric. In the present study, composites were fabricated with lower polymer viscosity by using solution impregnation [5].

Another concern in many aircraft applications is the wear and damage of composite surfaces caused by solid particles in the air [6], which can lead to lengthy maintenance, security risks, and other serious problems [7]. Thus, engineering materials must not only have high specific strength but also resist wear and damage.

For the past few years, many researchers have investigated how highly heat-resistant thermoplastics and their composites eroded by solid particles. For example, Sari et al. manufactured composites from unidirectional carbon fibers and PEI and investigated how their erosion behaviors changed with the particle velocity, impact angle, and surface roughness [8]. Miyazaki et al. made thermoplastic resins reinforced with short carbon fibers and analyzed how the solid-particle erosion behavior depended on the matrix (PI, PEEK), reinforcement fibers, impact angle, and particle velocity [9]. Harsha et al. studied composites made from PEEK and glass fibers, investigating how their fiber content and mechanical properties affected their erosion behavior [10].

The vast majority of these studied composite materials were reinforced with carbon fiber (CF) or glass fiber (GF) [7]. In contrast, there is little research on PBO (polybenzoxazole) fibers, aramid fibers, or other high-performance ductile fibers. These fibers are

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important to study mainly because aramid and other high-performance fibers have better erosion resistance than carbon fibers and glass fibers [6]. Also, the literature focuses on how unidirectional fiber orientation affects erosion behavior, but almost no work deals with how fabric orientation affects erosion behavior [3,11,12], and there are no convenient methods to predict the erosion rate of composites made from high-performance ductile fabrics. With a mathematical model, erosion rates can be predicted with less need for experiments; however, studying the erosion of these composites currently demands substantial time, energy, and materials.

In the present paper, we attempted to fill these gaps. By studying how changes in fabric orientation affected the erosion behavior of composites from an energy perspective, a mathematical model of the erosion rate as a function of impact angle was developed. To verify this model, the erosion behaviors of composites reinforced with high-performance ductile fabrics was studied, and then compared those experimental findings with our predictions. To elucidate the erosion mechanism of ductile materials, the damaged surfaces of one type of composite with scanning electron microscopy was analyzed.

2. Material and methods

2.1. Materials

The reinforcing fabric was PBO, a rigid-rod isotropic crystalline polymer (Toyobo Co., Ltd., Osaka, Japan). It has many advantages over traditional polymers—including high tensile strength, good fatigue resistance, and good resistance to corrosion, heat, chemicals, and salt water—so it has been used in many advanced fields such as the airline, marine, and space industries [13]. PBO fiber has a tensile strength of 5.8 GPa and a modulus of 270 GPa.

Two types of thermoplastic matrix were used: polyetherimide (PEI; Product Number 700193, Sigma-Aldrich Co. LLC., Missouri, USA; melting point = 280 °C) and polyethylene terephthalate (PET; Toyobo Co., Ltd., Osaka, Japan; glass transition temperature = 78 °C, softening point = 185 °C). PEI and PET were chosen so that we could verify that our mathematical model worked with both composites made from super engineering plastics (e.g., PEI) and composites made from common thermoplastic resins (e.g., PET).

The solvent for both PEI and PET was N-methyl-2-pyrrolidone (NMP; Kanto Chemical, Tokyo, Japan).

2.2. Manufacture of composite materials

To obtain a resin solution with low viscosity, PEI or PET (20 wt%) was dissolved in NMP with a hotplate magnetic stirrer (Coring PC-420D) at 60 °C for ~24 h. To adequately impregnate the fabric and evenly distribute the resin on the fabric surface, the fabric was pre-impregnated by using hand lay-up. This pre-impregnated fabric was placed in a vacuum oven at 220 °C to evaporate the solvent. After evaporation, the fabric surface was uneven, so it was smoothed with a hot press (table-type test press, SA-302, Tester Sangyo Co. Ltd., Tokyo, Japan) at 0.12 MPa and 200 °C (PET) or 290 °C (PEI) for 10 min. Finally, each prepreg sheet was cut to fit a metallic mold, placed in the mold, and pressed in it at 3.74 MPa for 30 min at 200 °C (PET) or 290 °C (PEI). Finally, the mold was allowed to cool to ambient temperature, producing the final composite.

2.3. Scanning electron microscopy (SEM)

After eroding the composites with solid particles, their damaged surfaces were studied with scanning electron microscopy (JSM-6010LA In Touch Scope, EOL Co. Ltd., Tokyo, Japan). To reduce surface charging, the samples were sputtered with Au in an Ar atmosphere.

2.4. Erosion behavior

The solid-particle erosion test rig was equipped with an air-gun nozzle (NAB-11-6; Trusco Nakayama Co. Ltd., Tokyo, Japan) with an inner diameter of 5.35 mm. Because the erosion rate decreases sharply with decreasing particle size and may even become zero at some nanozero threshold particle size, of order of 1–2 μm [14], on the other hand, once particle size beyond a critical particle size, it no longer belongs to wear but belongs to impact. Therefore, the solid particles were angular alumina with an average diameter of 37.7 ± 11.2 μm, fed by a micro-feeder (ME-1; Tsutsui Rikagaku Kikai Co. Ltd., Tokyo, Japan) at an average feed rate of 0.035 g/s. Because high velocity of erodent particles lead to higher erosion rates, to accelerate experimental process, an air compressor (Sulesanll, AS4PD-6, Kobe Steel, Ltd. Kobe, Japan) produced air with a high impact velocity of 127.4 m/s, which propelled the alumina toward the specimen to cause erosion wear. The distance between the air-gun nozzle and the specimen was 40 mm. To prevent the environment from influencing the experimental results, all erosion tests were performed under constant temperature (20 ± 1 °C) and humidity (65 ± 5%). Specimens of the prepared composites, which had lateral dimensions of 30 × 30 mm and a thickness of 1.2–2 mm, were held at various impact angles α (15°, 30°, 45°, 60°, 75°, and 90°), the angle between the air flow and the horizontal axis of the specimen. Composites with various fabric orientations β (0°, 15°, 30°, and 45°) were also produced to study how it affected erosion behavior. The fabric orientation was the angle between the central axis of the metal stage, used to fix samples, and the warp of the fabric. The erosion time was set to 30 min to make the experimental results more obvious.

For each composite, five tests were done on separate, identical specimens to calculate average results. The erosion rate was calculated according to the weight loss: $\Delta W_c/\Delta W_p$, where ΔW_c is the change in specimen weight after wear, compared with before, and ΔW_p is the total weight of solid particles used in the erosion test. A higher erosion rate means worse erosion resistance.

2.5. Measurement of air velocity

Pitot tube and PW type pressure gauge were used to measure the speed of air. Schematic diagram of this test method is shown in Fig. 1.

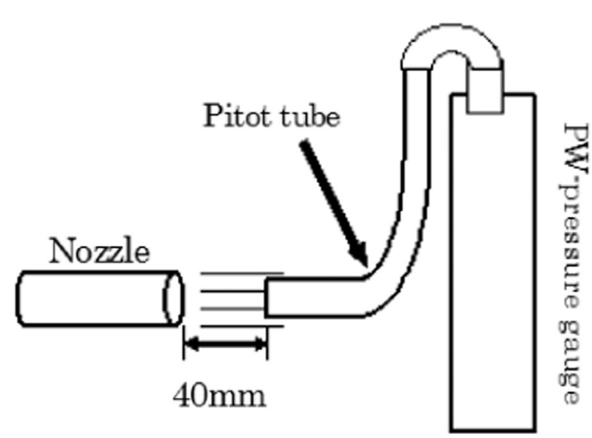

Fig. 1. Measurement of air velocity.